Preliminary 3D Modelling of Structural behaviour of Face Bolting and Umbrella Arch in Tunneling

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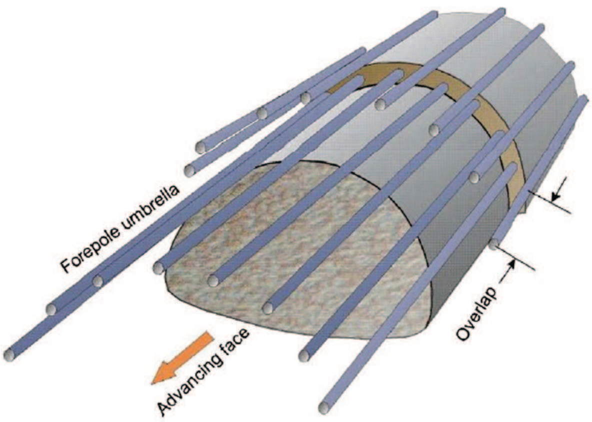
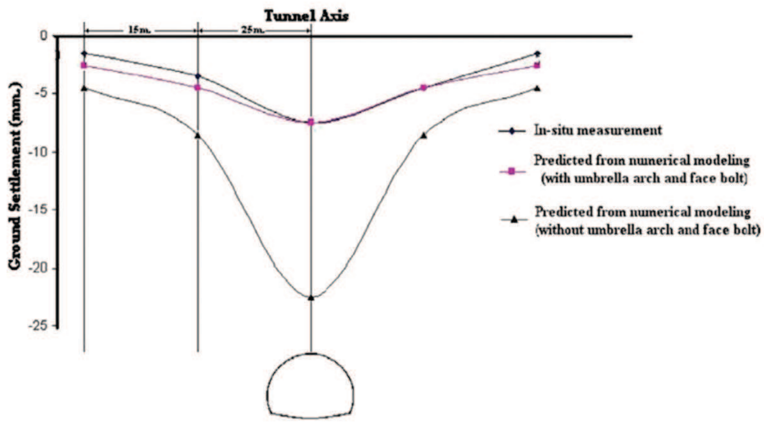
Umbrella arch and face bolting are two reinforcement technics used in tunnelling (NATM conventional tunnelling), especially for low-depth tunnels (H/D=1 to 5) in poorly consolidated soils. The arch is built by setting pipes around the contour line of the tunnel face prior to excavation, while bolting consists in setting and sealing long fiberglass or metallic rods at the tunnel face. The bolts provide improved mechanical properties to the ground that is to be excavated and they are gradually destroyed as the excavation progresses, whereas the arch brings stability to the whole face area and is left as a permanent reinforcement. In this context, 3D modelling of these tunnels and their reinforcement is essential to predict surface settlements and an important tool to validate appropriate tunnel designs.

Face bolts act essentially in tension but they may also be subjected to bending depending on the bolting density and the location of bolts in the tunnel cross section. They are designed to ensure the face stability and reduce the extrusion. In the literature the effect of an umbrella arch in tunnel stabilization has not been as well documented as face bolting.

Most studies agree on the improvements brought by the face bolts regarding surface settlements and face stability. Though, some authors point out that the umbrella arch may only provide better global stability. This may depend on the surrounding ground characteristics (hard or soft rocks, etc.), on the applied arch tilt and on the connection type used to hang the arch pipes to the tunnel steel ribs. Through a numerical analysis, Prountzopoulos (2011) showed how the umbrella arch could provide a good protection against local instabilities which are rather common in soft grounds or fractured rocks. Similar concluding

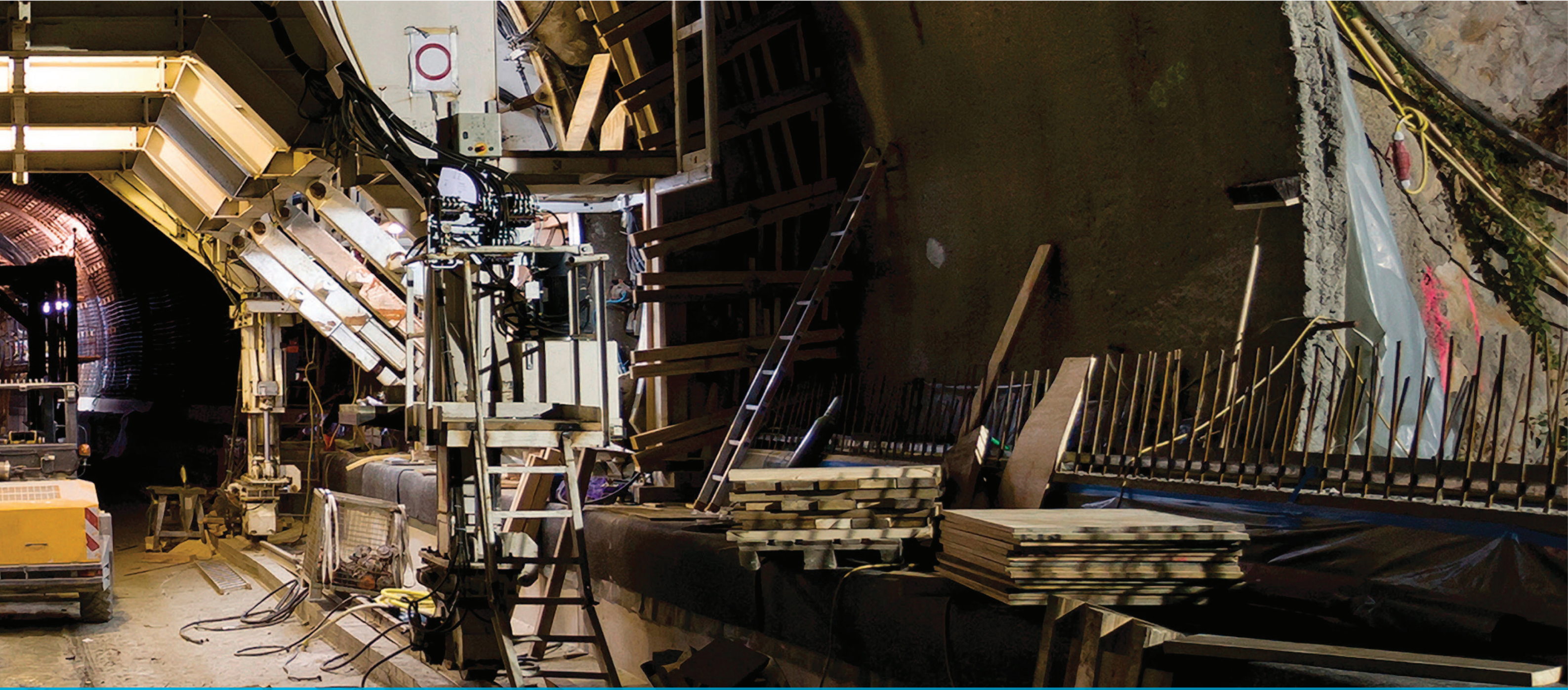


(a) Umbrella arch reinforcement



(b) Effect of reinforcements on settlements

Figure 1: Tunnel reinforcements and settlements (Aksoy and Onargan, 2010)



remarks were highlighted by Janin (2012): while the face bolting undergoes tension loads to improve face stability and reduce settlements, the umbrella arch mainly absorbs bending moments but does not affect surface settlements significantly.

Aksoy and Onargan (2010) concluded that an umbrella arch could be more efficient in grounds with poor mechanical properties. Figure 1 shows the efficiency of the combined system of both face bolting and umbrella arch in soft rocks (Ankara argillite, RQD<10%).

In order to verify above-mentioned findings and to examine the mechanical behaviour of each reinforcement element a parametric study was performed using the PLAXIS 3D software.
In the context of face bolting and the umbrella arch reinforcement, it is obvious that a realistic numerical modelling should be done in 3D configuration. PLAXIS 3D software was chosen because it includes in its library firstly, the Hardening Soil constitutive model (HSM) adapted to the rheology of studied soils (normally-consolidated soils due to small depth of tunnelling), and secondly an appropriate structural element to model the used bolts. The latter one is a beam element entitled "embedded pile" which is able to take into account the soil-bolt interface to study closely the behaviour of reinforcement. This software also has a quick and easy automatic mesh generation tool.

1. Base case

The analysis was conducted on the South tube of Toulon tunnel that is the tunnel on which Janin (2012) based his Phd Thesis. This tunnel was chosen, as it is well documented and appropriate to the study of settlements in low-depth tunnelling. Similar ground properties (c= 20kPa, φ=30°) and dimensions were used in order to compare results with Janin's model. Though the geometry was slightly simplified to a circular and constant tunnel section. The staged construction of Plaxis 3D (staged-step features) was used, with 3m-long processing cuts. The tunnel surface at the most recent cut is modelled by plate elements (with mechanical properties representative of shotcrete of 0.3m thickness). A layer of shotcrete is also sprayed on the face at every stage. The bolts are partially renewed every 3m. These bolts are 18-m long, and their properties are collected in table 1 together with other used reinforcements. Figure 2 shows the geometry of the tunnel and the vertical displacements caused by the excavation.

2. Modelling of the tunnel face bolting

This study investigated first the impact of bolting density on surface settlements. As shown in figure 3, settlements decrease while increasing bolting density (d = number of bolts per square meter at the tunnel face) even though this effect is less significant if we keep increasing this density. Here, bolts are modelled by "embedded pile" elements, which is discussed in the following.

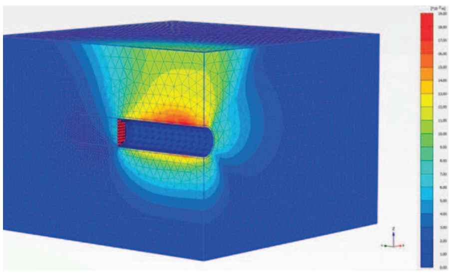


Figure 2: Geometry, mesh and vertical displacements of the tunnel surroundings

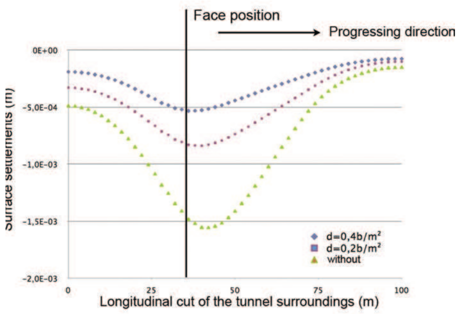


Figure 3: Impact of bolt density: partial settlement depression for a 3m-long cut for 0.4 bolt/m², 0.2 bolt/m² and without bolts

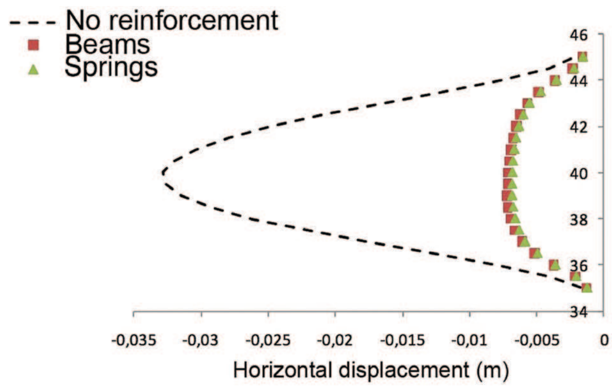
	E(GPa)	S(m²)	I(m⁴)	L(m)
Face bolt	210	0.448×10^{-3}	0.0327×10^{-6}	18
Umbrella arch	210	2.036×10^{-3}	1.689×10^{-4}	9
Shotcrete	1.35	-	-	3

Table 1: Characteristics of used reinforcements

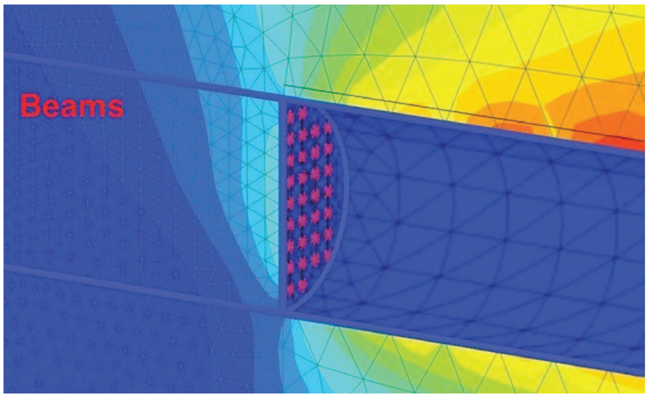
Figure 4 shows the impact of face bolting on extrusion of the tunnel face. At this stage, the face bolts were modelled by either beam or spring structural elements (fixed-end spring element, is able to consider only the axial forces). Figure 4a shows widely favourable effect of face bolting on extrusion decrease (face stabilization). At a significant bolting density, the results remain the same regardless the sort of element used to model the bolts.

Modelling bolts by "embedded pile" elements (beams with friction interface law) can be very useful to characterize the nature of undergone loads. Figures 5 and 6 show stresses (axial, mobilized friction and shear) and strains (deformed shape) profiles along the bolts, depending on the location of the bolts and the bolting density.
For a bolt located at the center of tunnel section, a low bolting density results in an important axial stress, mobilized friction and the shearing stress is significant nearby the face. On the contrary, at a higher bolting density, friction is mobilized on more bolts and then becomes less significant as the axial stress.

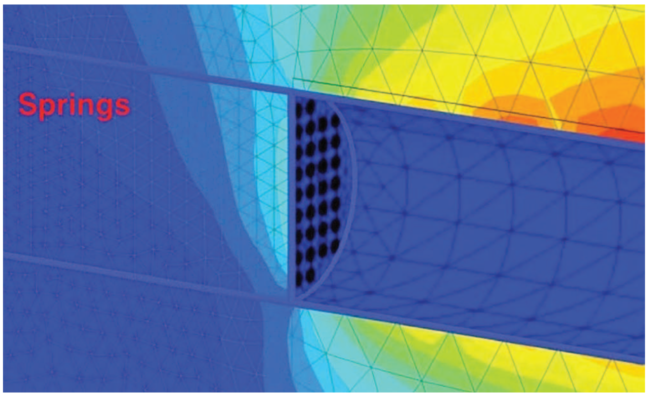
For a given bolting density, different profiles were observed, depending on the location of bolts on the tunnel face. Bolts located at the top of the face experience much more bending moments, especially nearby the face.



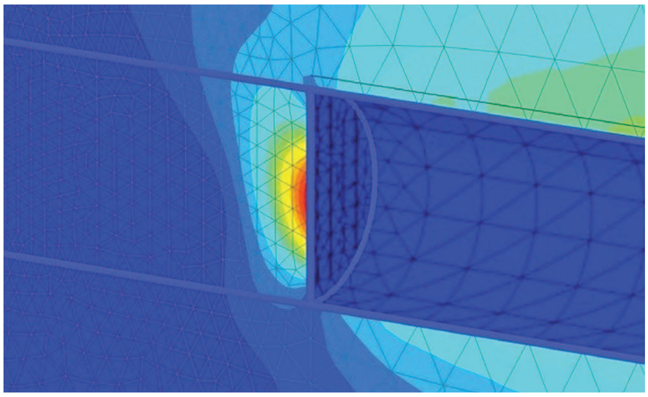
(a) Horizontal displacements at the face



(b) Modelling bolts with beam elements

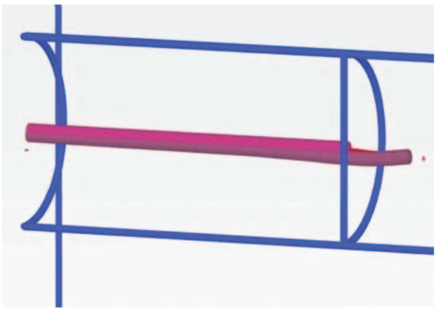


(c) Modelling bolts with spring elements

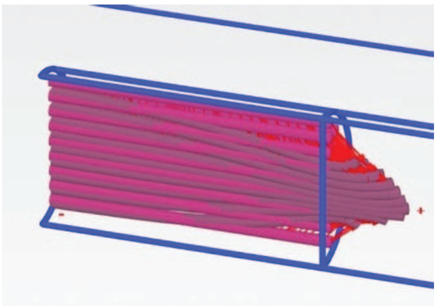


(d) No face reinforcement

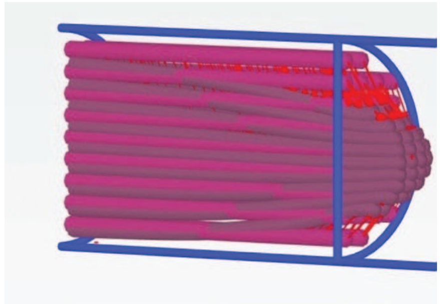
Figure 4: Impact of face reinforcement modelling: horizontal (a) and normalized (b, c, d) displacements



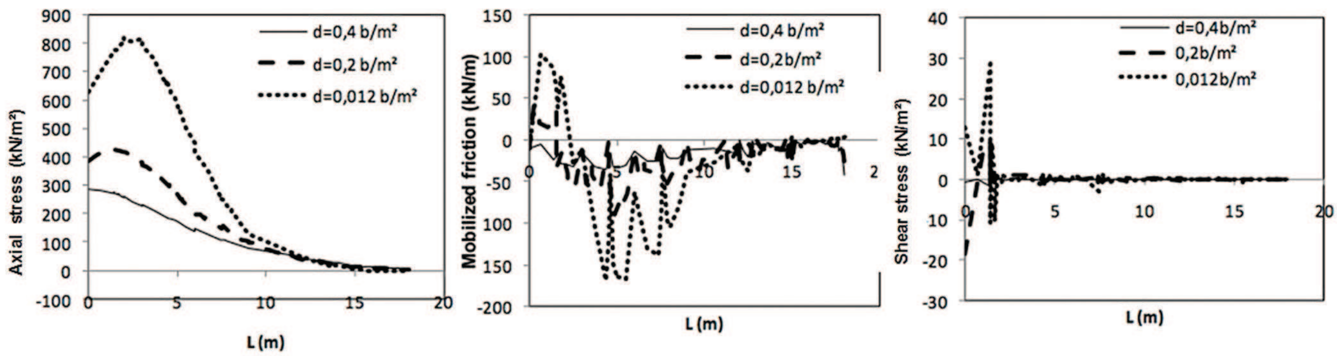
(a) Density = 0,012 b/m²



(b) Density = 0,2 b/m²

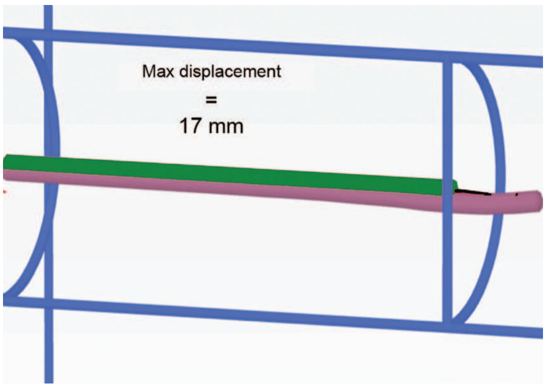


(c) Density = 0,4 b/m²

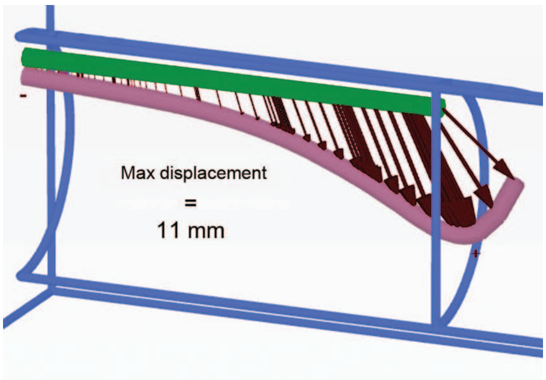


(d) Stresses on a bolt in the middle of the face, depending on bolting density

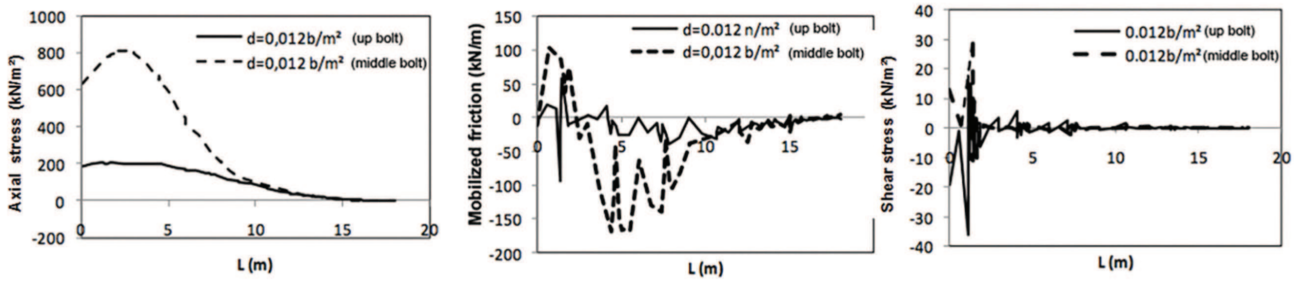
Figure 5: Impact of bolting density on strains and stresses



(a) Middle bolt, density = 0,012 b/m2



(b) Up bolt, density = 0,012 b/m2



(c) Stresses on a bolt depending on its position in the face

Figure 6: Impact of bolt positioning on strains and stresses

Bolts located at the top of the face experience much more bending moments, especially nearby the face.

On the contrary, axial stress is lower at the top as well as the mobilized friction. The central bolt undergoes a high axial stress as well as mobilized friction where lower shear stresses are generated. Regardless the location of the bolts or the bolting density, all the bolts showed a positive axial stress at the face. This seems contradictory with the boundary conditions (pressure inside the tunnel is 1 atm and therefore axial stress at the face should be null). It can actually be explained by the presence of the shotcrete layer covering the face.

3. Modelling of the umbrella arch

The same kind of parametric study was conducted for the umbrella arch. The geometry of the arch and its properties were the same as Janin's for the Toulon base case. The arch was made of 13 pipes of 18m length. Each pipe was spaced 50 cm from the next and tilted by 6°. All were renewed every 9m. The characteristics of used tubes for the umbrella arch are collected in table1. Figure 7 shows the geometry of the tunnel with the umbrella arch and the vertical displacements generated by the excavation.

Figure 8 shows the surface settlement for a 60m long tunnel construction. Settlements were reduced by about 5% with the umbrella pipes. This result confirms Janin's conclusion: the arch does not seem to impact significantly the surface settlements. Increasing the diameter of the pipes does not seem to modify significantly the result either (depicted by D2 on figure 8). It is well known that the pipes of the arch undergo essentially bending moments. Figure 9 confirms this point and locates the highest bending moments close to the pipe heads. This last point is important because it means any inaccuracy in the numerical modelling of that sensitive region could impact the local stability of tunnel. In particular, the hanging point between the pipes and the tunnel steel rib should be modelled carefully.

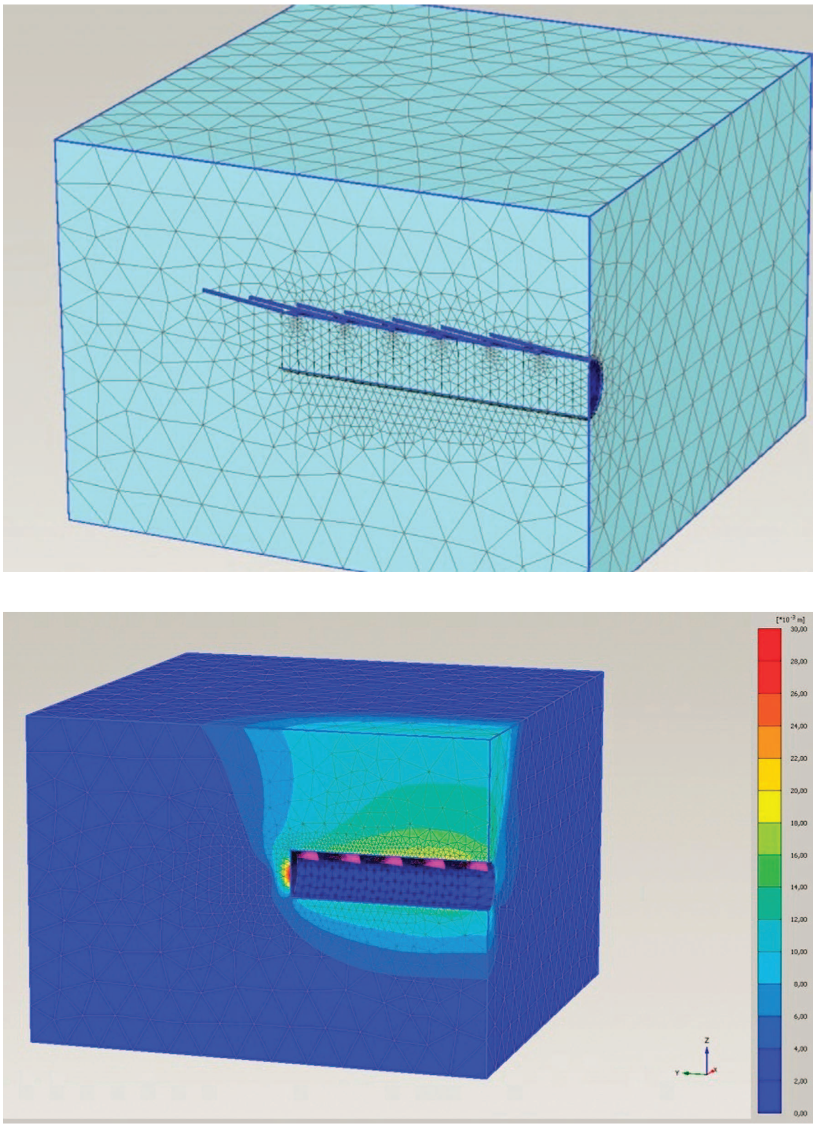


Figure 7: Geometry, mesh and vertical displacements of the tunnel surroundings with umbrella pipe reinforcement

Conclusion

The study on structural behaviour of the face bolting showed that the bolts work essentially in tension, but may be subject to bending according to their position and density.

A beam element is therefore more appropriate than an anchor element. Yet, the axial load in the bolts remains the most important, suggesting the importance of the bolt-ground interface considered in the numerical analysis. This interface was taken into account using PLAXIS 3D "embedded piles" elements which permitted the estimation of the mobilized friction and the shear stress through the bolts.

The parametric study on the arch umbrella confirmed Janin's results. However the connection between the pipes and the tunnel wall seems to play an important role.

It should be noted that a circular constant geometry was used to model the tunnel in this study, where a tunnel with a variable section would provide a better rigidity (connection quality) between the pipes and the tunnel, as depicted in figure 1(a).

References

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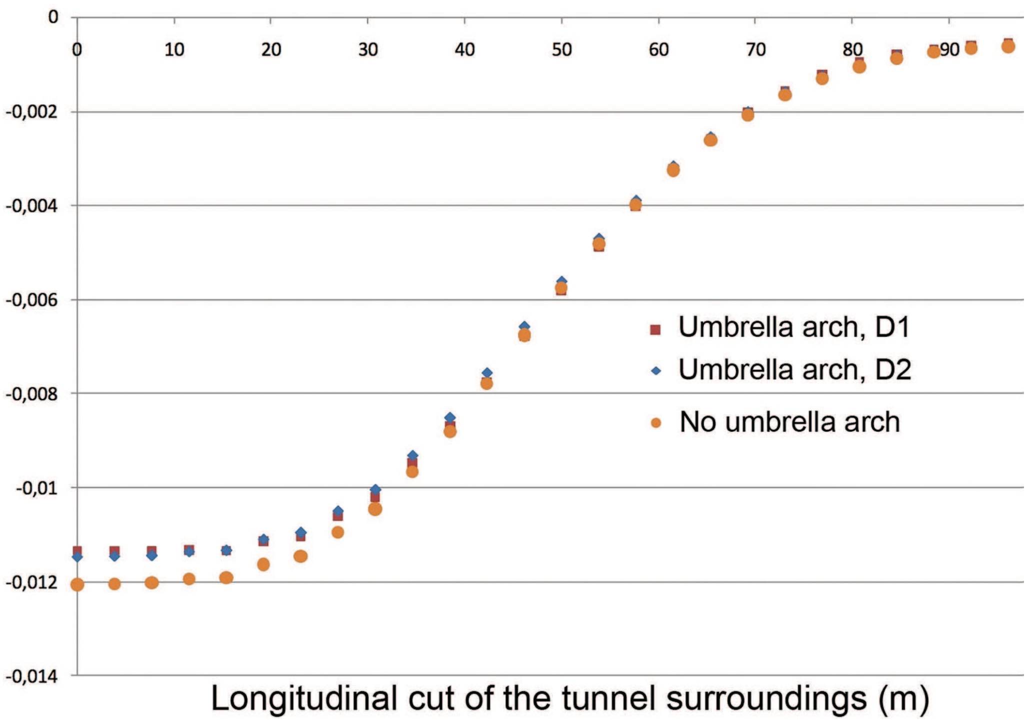

Figure 8: Impact of umbrella-arch reinforcement on cumulative surface settlement

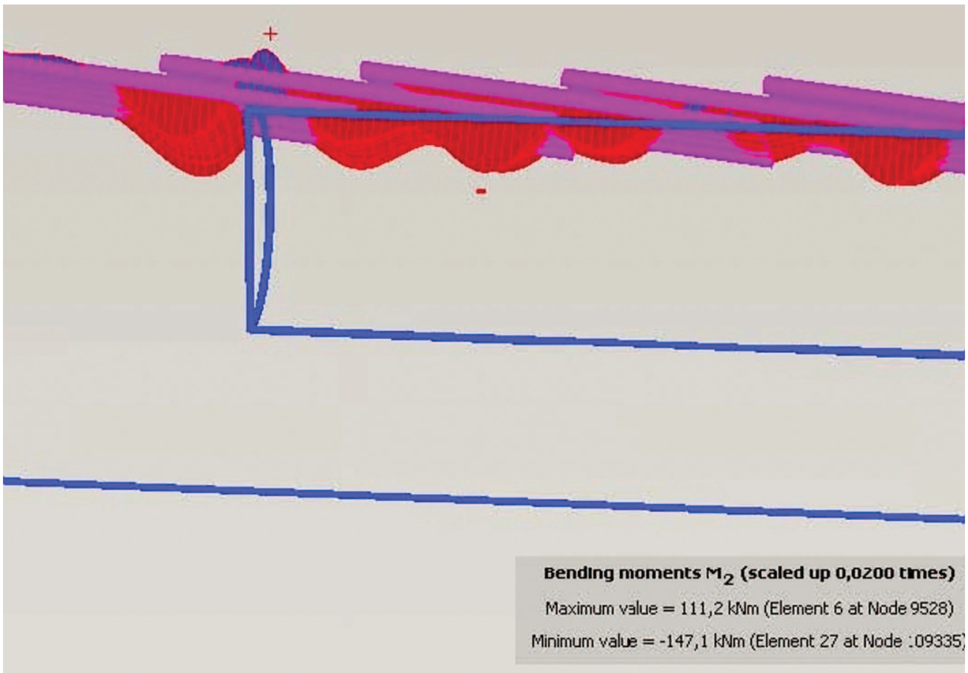

Figure 9: Bending moment in the umbrella arch